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Experimental Consequences of R-Parity Breaking*

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Abstract

We consider the consequences of R parity breaking in low energy supersymmetric models. We discuss the new phenomenology expected in this class of models and compare it with the predictions of the R conserving supersymmetric theories.

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1 Introduction

Most phenomenological studies of supersymmetric models have been done assuming an effective low-energy SUSY theory in which baryon and lepton number are absolutely conserved. This requirement is not dictated by the supersymmetry, but must be imposed by hand. In this note, we examine the experimental consequences of relaxing this assumption.

2 What is R-Parity?

Supersymmetric theories have an additively conserved R quantum number which can be defined such that left chiral superfields Φ have $R = 2/3$, vector superfields V have $R = 0$, and the anti-commuting $\theta(\bar{\theta})$ variable has $R = 1 (R = -1)$.[1] The superfields Φ and V can be written in terms of component fields as,

$$\begin{aligned} \Phi &= A + \sqrt{2}\theta\psi + \theta\theta\mathcal{F} \\ V &= -\theta\sigma^m\bar{\theta}v_m + i\theta\theta\bar{\theta}\bar{\lambda} - i\bar{\theta}\bar{\theta}\theta\lambda + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}D \end{aligned} \tag{1}$$

where A, ψ, and $\mathcal{F}$ are the scalar, Majorana fermion, and auxiliary component fields of Φ and v_m, λ, and D are the vector, Majorana fermion, and auxiliary component fields of V.[2]

In a supersymmetric Lagrangian, global R invariance is conserved (modulo 2) and the allowed renormalizable terms in the Lagrangian are,

$$\Phi^\dagger e^V \Phi\mid_D, \quad WW\mid_F, \quad \Phi^3\mid_F, \quad (\Phi^\dagger)^3\mid_F, \quad V_D \tag{2}$$

where $WW\mid_F$ contains the kinetic terms for v_m and λ. The F and D terms are defined to be the $\theta\theta$ and $\theta\theta\bar{\theta}\bar{\theta}$ contributions to the expansion of a product of superfields in terms of component fields. For example,

$$\begin{aligned}\Phi_a\Phi_b\Phi_c &= A_aA_bA_c + \sqrt{2}\theta(\psi_aA_bA_c + \psi_bA_cA_a + \psi_cA_aA_b)\\ &+ \theta\theta(-\psi_a\psi_bA_c - \psi_b\psi_cA_a - \psi_c\psi_aA_b)\\ &+ \theta\theta(\mathcal{F}_aA_bA_c + \mathcal{F}_bA_cA_a + \mathcal{F}_cA_aA_b)\end{aligned} \tag{3}$$

and so

$$\begin{aligned}\Phi_a\Phi_b\Phi_c\,|_F = &-\psi_a\psi_bA_c - \psi_b\psi_cA_a - \psi_c\psi_aA_b\\ &+ \mathcal{F}_aA_bA_c + \mathcal{F}_bA_cA_a + \mathcal{F}_cA_aA_b.\end{aligned} \tag{4}$$

In a renormalizable Lagrangian, R invariance can be broken only by terms of the form,

$$(\Phi_1\Phi_2)\,|_F \quad \text{or} \quad (\Phi)\,|_F\,. \tag{5}$$

In a supersymmetric version of the Weinberg-Salam model, R parity is certainly broken by the vacuum expectation values of the Higgs fields, $\langle H\rangle$ and $\langle H'\rangle$, since the Higgs fields have $R = 2/3$. These VEVs must be non-zero in order to break $SU(2)_L \times U(1)_Y$ and to give the quarks and leptons masses. R parity is also broken by the Majorana mass terms of the model,

$$\mathcal{L}_M = m(\lambda\lambda + \bar{\lambda}\bar{\lambda}) \tag{6}$$

since λ has $R = 1$. Such mass terms must be present because cosmological limits prohibit a massless photino or gluino.[3]

In most supersymmetric models, however, there remains a conserved multiplicative quantum number which we call $\tilde{R}$ parity. Frequently, $\tilde{R}$ parity is a linear combination of R parity and discrete symmetries of the model. The $\tilde{R}$ quantum number is $+1$ for all of the known fields and -1 for their supersymmetric partners. The $\tilde{R}$ parity of a particle is,

$$\tilde{R} = (-1)^{2S+3B+L} \tag{7}$$

where S, B, and L are the spin, baryon number, and lepton number of a particle. Note that the gaugino mass terms and the VEVs of the Higgs fields both conserve $\tilde{R}$.

An immediate consequence of $\tilde{R}$ conservation is associated production – there are always an even number of SUSY particles produced in hadronic or e^+e^- interactions. Also, $\tilde{R}$ conservation forbids mass mixing between the SUSY particles and the known particles.

3 Why Break $\tilde{R}$ Parity?

If $\tilde{R}$ parity is conserved, then baryon and lepton number are automatically conserved. In the non-supersymmetric $SU(3) \times SU(2) \times U(1)$ model, the gauge symmetries alone prohibit the addition of any terms to the Lagrangian which break baryon or lepton number. In a supersymmetric model, however, $\tilde{R}$ parity, and hence B and/or L, can be broken either spontaneously or explicitly.[4,5]

If we construct the most general effective low energy supersymmetric Lagrangian consistent with the gauge symmetries, then we can include terms of the form,

$$
\begin{aligned}
\mathcal{L} = & -m_a^2 \phi_H \tilde{\phi}_{La} - C_a(\psi_{u_{La}} \psi_{\bar{d}_{La}} \tilde{\phi}_{e_{La}} \\
& + \psi_{d_{La}} \psi_{\bar{d}_{La}} \tilde{\phi}_{\nu_{La}} + \cdots) \\
& - D_a(\psi_{e_{La}} \psi_{\bar{e}_{La}} \tilde{\phi}_{\nu_{La}} + \cdots) \\
& - E_a(\psi_{\bar{u}_{La}} \psi_{\bar{d}_{La}} \tilde{\phi}_{\bar{d}_{La}} + \cdots) \\
& \quad + \text{h.c.}
\end{aligned} \tag{8}
$$

where the ... indicate SUSY permutations of the fields and the coefficients C_a, D_a, and E_a are arbitrary. ($\psi_{u_{La}}$ is the left-handed charge 2/3 quark of generation a and $\phi_{u_{La}}$ is the associated scalar, etc. and all of the SUSY fields are denoted by tildes. The notation is that of Ref. 5.) For simplicity, we have assumed that the $\tilde{R}$ violating terms of Eq. (8) are diagonal in generation space.

To forbid the Lagrangian of Eq. (8), it is necessary to impose B or L (or $\tilde{R}$) conservation or some other discrete symmetry by hand. For example, an invariance under $H \to -H, Q \to -Q, \bar{U} \to -\bar{U}$, and $\bar{E} \to -\bar{E}$ does not allow any $\tilde{R}$ violating terms in the Lagrangian.

$\tilde{R}$ conservation can also be violated by allowing the scalar partners of the neutrinos to obtain VEVs. These VEVs introduce mass mixing between the SUSY particles and the ordinary particles. There will be mixing between the wino, Higgsino, and charged leptons and also between the photino, zino, neutral Higgsinos, and neutrinos. This mixing will destroy the property of associated production of SUSY particles and allow processes such as $pp \rightarrow \tau\tilde{g}$, etc. (Cross sections for $p\bar{p} \rightarrow \tau\tilde{g}$ and $p\bar{p} \rightarrow \tau\tilde{\gamma}$ at $\sqrt{s} = 540$ GeV are given in Ref. 5).

In the absence of any compelling models of low energy supersymmetry it is important to examine the consequences of $\tilde{R}$ violation on the experimental predictions.

4 Consequences of $\widetilde{R}$ Parity Breaking

Lepton number violating interactions will allow numerous rare processes such as $\pi \rightarrow e\nu$, $\mu \rightarrow e\gamma$, and $\mu \rightarrow 3e$, for example. Unfortunately, the limits obtained by looking at these processes are not stringent since they always involve the exchange of at least one SUSY particle of unknown mass. For scalar SUSY masses near 1 TeV, experimental restrictions allow $C_a \sim 10^{-3}$ and $D_a \sim 10^{-3}$.[4,5]

$\tilde{R}$ parity violation also allows one of the neutrinos to obtain a Majorana mass. Assuming that this is ν_τ and that $m_{\nu_\tau} < 55$ GeV,[6] we have,

$$\sqrt{\sum_a \tilde{v}_a^2} < 14 \text{ GeV} \tag{9}$$

for scalar SUSY masses near 1 TeV. ($\tilde{v}_a$ are the scalar sneutrino VEVs).

Finally, the term proportional to E_a in Eq. (8) allows proton decay which requires $E_1 \leq 10^{-35}$ for scalar masses near 1 TeV and $C_1 \sim 10^{-3}$.

In most SUSY models, the lightest supersymmetric particle is taken to be the photino and it is assumed to be stable. However, in theories with $\tilde{R}$ violation, the photino can decay in numerous ways,

$$i)\ \tilde{\gamma} \rightarrow \gamma\nu$$

$$ii)\ \tilde{\gamma} \rightarrow q\bar{q}\nu$$

$$iii)\ \tilde{\gamma} \rightarrow u\bar{d}e^-$$

$$iv)\ \tilde{\gamma} \rightarrow e^+ e^- \nu. \quad (10)$$

In addition, the sneutrino can decay to a neutrino, anti-neutrino pair. The $\tilde{\gamma}$ lifetime depends on the parameters of Eq. (8) and on the sneutrino VEVs and is given in Ref. 5. However, for a wide range of reasonable parameters the photino will decay within the detector.

As an example, consider the process $p\bar{p} \rightarrow \tilde{g}\tilde{g}$. If the photino is stable (and lighter than the gluino), then we expect $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$. Then the signal for $p\bar{p} \rightarrow \tilde{g}\tilde{g}$ is ≤ 4 jets plus missing p_T. If the photino decays to $\gamma\nu$, then the signal will be ≤ 4 jets accompanied by 2 photons, but the $\tilde{\gamma}$ decay will degrade the missing p_T signal. If $\tilde{\gamma} \rightarrow q\bar{q}\nu$, then there will be ≤ 8 jets. In all cases, the decay of the photino leads to a degraded missing p_T signal which yields significantly smaller cross sections since fewer events will pass a given missing p_T cut. For example, only about 1/100 as many events pass a simulation of the UA1 cuts if $\tilde{\gamma} \rightarrow q\bar{q}\nu$ as for a stable photino.

The different photino decay modes change the ratio of 1- to 2-jet events. In Fig. 1, we show the 1- and 2-jet cross sections for gluino pair production at $\sqrt{s} = 540$ GeV as a function of the gluino mass (and for fixed squark mass) for each of the assumed $\tilde{\gamma}$ decay patterns.[7] The largest jet cross sections result when the photino is stable, with the two jet cross section becoming larger than the one jet cross section for a gluino mass between 40 and 50 GeV. The jet cross sections are approximately an order of magnitude smaller when $\tilde{\gamma} \rightarrow \gamma\nu$. This is because we have included the photon energy in our definition of the total transverse energy, E_T, which means that fewer of the events can pass the $E_T^{missing}$ cut. The jet cross sections are considerably smaller when $\tilde{\gamma} \rightarrow q\bar{q}\nu$ with the 2-jet cross section always dominating over the 1-jet cross section. In this case, the 3-jet cross section becomes dominant for gluino masses greater than about 60 GeV.

5 Conclusion

In supersymmetric models with $\tilde{R}$ parity violation, the phenomenology will be quite different from the usual SUSY theories. Single production of SUSY particles will lead to spectacular new signals. The most striking new signature, however, will be the decay of the photino which leads to degraded missing p_T signatures. This will considerably complicate the search for supersymmetry!

6 Acknowledgments

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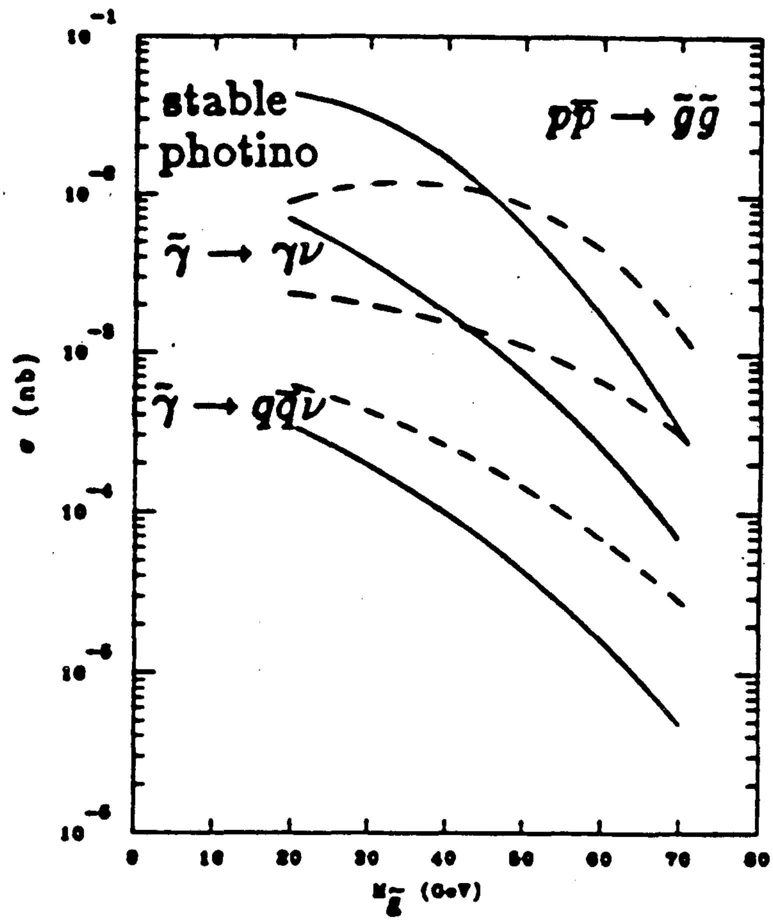

Fig 1. Jet cross sections for the reaction $p\bar{p} \to \tilde{g}\tilde{g}$ at $\sqrt{s} = 540$ GeV. The solid lines are the one jet cross sections and the dashed lines are the two jet cross sections. The three sets of curves represent a stable $\tilde{\gamma}$, $\tilde{\gamma} \to \gamma\nu$, and $\tilde{\gamma} \to q\bar{q}\nu$.

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